The Origin of X-shaped Radio Galaxies: Clues from the Z-symmetric Secondary Lobes

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ABSTRACT

Existing radio images of a few X-shaped radio galaxies reveal Z-symmetric morphologies in their weaker secondary lobes which cannot be naturally explained by either the galactic merger or radio-lobe backflow scenarios, the two dominant models for these X-shaped radio sources. We show that the merger picture can explain these morphologies provided one takes into account that, prior to the coalescence of their supermassive black holes, the smaller galaxy releases significant amounts of gas into the ISM of the dominant active galaxy. This rotating gas, whose angular momentum axis will typically not be aligned with the original jets, is likely to provide sufficient ram pressure at a distance $\sim$10 kpc from the nucleus to bend the extant jets emerging from the central engine, thus producing a Z-symmetry in the pair of radio lobes. Once the two black holes have coalesced some 10^7 yr later, a rapid reorientation of the jets along a direction close to that of the orbital angular momentum of the swallowed galaxy relative to the primary galaxy would create the younger primary lobes of the X-shaped radio galaxy.

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This picture naturally explains why such sources typically have powers close to the FR I/II break. We suggest that purely Z-symmetric radio sources are often en route to coalescence and the concomitant emission of substantial gravitational radiation, while X-shaped ones have already merged and radiated.

Subject headings: galaxies: active — galaxies: jets — gravitational waves — radio continuum: galaxies

1. Introduction

Although the characteristic morphology of powerful (FR II) radio galaxies is a pair of radio lobes containing hotspots straddling the parent elliptical galaxy (Fanaroff & Riley 1974), almost 10% of the weaker FR II radio galaxies have a strikingly different morphology: they possess two misaligned pairs of radio lobes of comparable extent (e.g. Leahy & Parma 1992). While the existence of such X-shaped, also called winged, radio galaxies (RGs) was already recognized three decades ago (e.g. 3C 315, Högbom & Carlson 1974), it is only very recently that they have shot into prominence. This is due to the growing realization that the origin of the X-shaped radio morphology may be a marker of the coalescence of two supermassive black holes (SMBH) previously hosted by a pair of merging galaxies.

Such an interaction can lead to a rapid realignment of the angular momentum, or spin-flip, of the active SMBH, accompanied by emission of gravitational radiation of high intensity and angular momentum (e.g. Rottmann 2001; Zier & Biermann 2001, 2002; Chirvasa 2002; Merritt & Ekers 2002; Biermann et al. 2003). In a related approach, Dennett-Thorpe et al. (2002) have concluded that a rapid jet reorientation could also arise from instabilities in the accretion disk, though they agreed that minor mergers were likely to be better explanations for the reorientations in 3C 223.1 and 3C 403, sources they studied in detail. A somewhat related suggestion was that of Ekers et al. (1978), who noted the possibility of a secular precession of the jets due to a mismatch between their direction and the galaxy axis.

An alternative and long discussed mechanism for the X-shaped morphology is based on the idea that the back-flowing plasma from the radio hotspots can be diverted due to pressure gradients in the external gas (e.g. Leahy & Williams 1984; Worrall, Birkinshaw & Cameron 1995). Arguing strongly for this general picture, Capetti et al. (2002) have recently pointed out that X-shaped radio structures occur preferentially in galaxies of high ellipticity and, furthermore, the secondary lobe pair (or wings) is usually closely aligned with the minor axis of the host galaxy, i.e., towards the steepest pressure gradient of the ambient medium as determined by the galaxy potential. Based on their two-dimensional hydrodynamical

simulations (which, however, assumed a reflection symmetry that artificially enhances the numerically observed perpendicular outflow), Capetti et al. (2002) have further argued that the principal driving mechanism for the backflow diversion, appearing as ordered outflows along the galaxy minor axes, is the over-pressure of the radio cocoon, which, aided by buoyancy forces, can conceivably lead to the secondary lobes growing as rapidly as the main lobe pair.

Clearly, a basic difference between the backflow-diversion and spin-flip scenarios is that whereas in the former case both the primary and the secondary lobe pairs are envisioned to form quasi-simultaneously, the creation of the secondary (in the sense of lacking hotspots) lobe pair in the spin-flip scenario occurs prior to the spin-flip event, while the currently active jets (i.e., after the spin-flip) feed the primary lobes, which usually contain hotspots, and are thus classified as FR II sources.

2. Rotating ISM and Z-symmetric jet bending

We wish to draw attention to an apparently hitherto unnoticed morphological feature of X-shaped RGs which is very difficult to reconcile with either of the two proposed models mentioned above. Inspection of the high resolution VLA maps of the prominent X-shaped RGs (XRGs) 3C 52 (Leahy & Williams 1984) and NGC 326 (e.g. Murgia et al. 2001) shows that the ridge lines of the two extended secondary lobes are not aligned with each other. The lobes are clearly offset from each other laterally by roughly their widths (Fig. 1), with the inner edges of the secondary lobes aligned with each other and with the galactic nucleus. Thus, instead of extending in diametrically opposite directions from the galactic nucleus, the secondary lobes exhibit an approximately Z-shaped symmetry about the nucleus. Since a rather special aspect angle, in addition to high angular resolution, is a prerequisite for being able to view such an offset, it is quite conceivable that a Z-symmetry of the secondary lobe pair is actually a common feature of XRGs; another possible example is 3C 223.1 (Capetti et al. 2002).

It is not obvious how the lateral offset of the secondary lobes, which gives rise to their Z-symmetry, can arise naturally either in the spin-flip case, or in the backflow-diversion model, particularly when the axes of the primary and secondary lobes are roughly orthogonal to each other, as they are in both of these cases. In a variant of the original backflow-diversion picture (e.g. Leahy & Williams 1984), the Z-symmetry of the secondary lobes could, conceivably, be enforced by the diversion of the backflow by a giant disk of denser material associated with the host galaxy and oriented roughly perpendicular to the primary radio axis (Gopal-Krishna & Wiita 2000). The existence of such *superdisks* has been inferred in several FR II radio

galaxies from the sharp strip-like emission gaps observed between their radio lobes (Gopal-Krishna & Wiita 2000). However, superdisks also seem to provide only a partial explanation for the Z-symmetries. Firstly, it is unclear how a nearly vertical infall of the back-flowing plasma onto the superdisk could lead to its diversion to just one side of the primary lobe axis. Furthermore, this mechanism could not explain what makes the plume-like secondary lobes as long as, or even longer, than the directly powered main lobes. In at least some cases this cannot be due to projection effects; e.g., for NGC 326 the jets are almost certainly close to the plane of the sky (Murgia et al. 2001).

To address these shortcomings, we propose a new model for the XRGs which encompasses an important modification to the spin-flip scenario. Basically, it takes into account the dynamical effect on the jets of the large-scale rotational field, which is naturally set up in the ambient medium, as the captured galaxy, along with its SMBH, spirals in towards the core of the RG. These gas motions can bend the original jets (existing prior to the SMBH coalescence) into a Z-symmetric shape. Eventually, the coalescence of the two SMBHs produces a concomitant spin-flip of the active SMBH; its jets then create a new pair of (essentially unbent primary) radio lobes.

Z-symmetric bending of radio jets/lobes on kiloparsec (or larger) scales is not a rare occurrence among radio galaxies, especially those of the FR I type (e.g. Miley 1980). A likely explanation for such morphology can be given in terms of a rotating ISM which can bend sufficiently 'soft' radio jets. A recent study of 21 nearby FR I RG hosts was able to detect significant rotation in the Hα emitting gas in the nuclear regions of 14 of them, and most of the remainder were essentially face-on (Noel-Storr et al. 2003); hence, significant amounts of rotating gas are very possibly ubiquitous in RG hosts. The rapidly rotating ISM can be associated with the kpc-scale disks (or partial rings) which now have been found around the nuclei of many early-type galaxies; in some cases these disks are able to survive long after the galaxy merger as regular H I structures (e.g. Oosterloo et al. 2002; Hibbard & van Gorkom 1996). Dense clouds containing both H I gas and molecular gas at radial distances of $\sim$10 kpc from the nucleus have been clearly detected in the nearest radio galaxy, Cen A (Schiminovich et al. 1994; Charmandaris, Combes & van der Hulst 2000). The association of these dense clouds with some of the stellar shells originally found by Malin (1979) and Malin, Quinn & Graham (1983) shows that they are remnants of a merged gas-rich galaxy. Charmandaris et al. (2000) showed that the association of these gaseous features with the stellar shells even at radial distances of many kpc can be understood within the standard picture of shell formation through galactic mergers (e.g. Quinn 1984), if one takes into account that the ISM of the merged galaxy is clumpy, and hence not highly dissipative.

The scenario of jet bending as a result of a jet–shell interaction was originally proposed

immediately after the discovery of optical shells (Gopal-Krishna & Chitre 1983) and discussed in detail in the context of Cen A (Gopal-Krishna & Saripalli 1984). This possibility was indirectly supported by numerical simulations of jets being bent by winds in both two-dimensional and three-dimensional simulations (e.g. Loken et al. 1995), and is strongly favored by the recent discoveries of H I and H_2 components of some of the stellar shells in Cen A, as mentioned above. The measured radial velocities of the two diametrically opposite molecular clouds straddling the active nucleus differ by 380 km s^{-1} (Charmandaris et al. 2000). While not all of this is likely due to rotational motion around the nucleus, it does indicate a rotational speed of $\sim$100 km s^{-1} for the clouds at a radial distance of $\sim$15 kpc from the nucleus. The diameter of these clouds is $\sim$3 kpc, and thus their estimated masses of $\sim 4 \times 10^7 M_\odot$ imply an average gas density $\sim 4 \times 10^{-2}$cm^{-3}. The corresponding sideways dynamical pressure acting on the jets, $p_{\rm dyn} = \rho_{\rm ISM} v_{\rm ISM}^2$, is thus $\sim 6 \times 10^{-12}$ dyne, with $\rho_{\rm ISM}$ the mean mass density of the clouds and $v_{\rm ISM}$ their rotational velocity. Independent estimates of the energy densities in the inner radio lobes, located roughly between 3 and 7 kpc from the galactic center, range from $1 - 9 \times 10^{-11}$ erg cm^{-3} (Gopal-Krishna & Saripalli 1984; Burns, Feigelson & Schreier 1983; Feigelson et al. 1981). In that the energy density in the jets should have declined somewhat by the time they propagate out to the distance of the clearly detected moving shells, the ram pressure the latter could exert is sufficient to bend the jets enough to deflect them into the giant lobes. Three-dimensional numerical simulations of light jets striking massive clouds with sizes several times the jet radius confirm that stable bendings of $>45°$ are possible (Higgins, O'Brien & Dunlop 1999; Wang, Wiita & Hooda 2000).

For NGC 326, Murgia et al. (2001) determine energy densities in the West wing of $\sim 8 \times 10^{-13}$ erg cm^{-3} and in the East wing of $\sim 3 \times 10^{-12}$ erg cm^{-3} in the regions where they are being bent. They point out that while the primary lobes are in rough equilibrium with respect to the surrounding intracluster medium, which has a pressure of roughly 5×10^{-12} dyne cm^{-2} (Worrall & Birkinshaw 2000), the wings appear underpressured even with respect to the ICM. In the case of NGC 326 no direct evidence is available as yet for the existence of gas clouds within the ISM (though its association with a dumbbell galaxy clearly points to a merger-prone environment, e.g. Colina & de Juan 1995), but if they are present and have properties similar to those in Cen A, then they would easily be able to bend the secondary lobes. For the XRGs 3C 52 and 3C 223.1, evidence for a recent galaxy merger exists in the form of dust disks detected on the HST images (de Koff et al. 1996).

More generally, one can obtain rough constraints on the necessary parameters of the rotating ISM with respect to those of the jets through the Euler equation applied to jet flows (e.g. O'Donoghue, Eilek & Owen 1993)

$$\rho v^2 / l_{\rm bend} \simeq \rho_{\rm ISM} v_{\rm ISM}^2 / l_{\rm pres}, \qquad (1)$$

where ρ is the density in the jet, v the flow velocity through it, l_{bend} the scale over which the jet bends, and l_{pres} is the length scale over which the ISM applies the pressure to the jet; this last quantity can be no less than the radius of the jet, $R_j \sim 1$ kpc. Assuming the clouds in Cen A as reasonable for the ISM and that the jet is sub-relativistic and made of ordinary proton-electron plasma (pair plasma jets would be easier to bend), we can normalize quantities as follows: $l_{b,1} = l_{\text{bend}}/10$ kpc, $l_{p,0} = l_{\text{pres}}/1$ kpc, $n_{\text{ISM},-1} = n_{\text{ISM}}/0.1$ cm^{-3}, $v_{\text{ISM},2} = v_{\text{ISM}}/100$ km s^{-1}. We then have, $nv^2 \simeq 10^4\, l_{b,1}\, l_{p,0}^{-1}\, n_{\text{ISM},-1}\, v_{\text{ISM},2}^2$, with the particle number density in the jet, n, in cm^{-3} and v in km s^{-1}. If the jet velocity is semi-relativistic on these scales, i.e., $v \sim 10^5$ km s^{-1}, we require $n \sim 10^{-6}$ cm^{-3} if bending is to be possible; this is a low, but certainly plausible, density. Somewhat higher densities in a bent jet can be accommodated if the jet flow is slower or if the ISM ram pressure is higher; however, if the jet thrust is very high, as is the case for powerful FR II sources, even a clumpy ISM will have little impact on the jets (Higgins et al. 1999; Wang et al. 2000).

3. Discussion and Conclusions

As discussed above, $\sim 10^7$ years before the merger of the two SMBHs, a thick disk or torus-like rotational field on the kpc scale can be expected to be established in the ISM of the RG, roughly along the orbital plane of the captured galaxy's core. For the interesting case when the infalling black hole with mass M_2 has a significant mass compared to the active SMBH with mass M_1 (say $M_2 > 0.5M_1$), the spin vector of the SMBH after the black holes' merger will be essentially along the orbital angular momentum vector of the captured black hole (Zier & Biermann 2002); but even if $M_2 \simeq 0.05M_1$, a significant reorientation of the SMBHs spin axis to a direction predominantly along the original orbital angular momentum is generally expected (Merritt & Ekers 2002). Since, prior to the merger, the jets of the RG will typically be oriented at a large angle to the orbital angular momentum vector, they would be subject to the sideways dynamic pressure exerted by the rotating ISM and would, consequently, develop a Z-symmetric distortion unless their kinetic power is quite high. Such distorted radio structures are detected in several nearby galaxies with radio jets, such as M84 (Laing & Bridle 1987), Cen A (Gopal-Krishna & Saripalli, 1984; Schiminovich et al. 1997) and IRAS 04210+0400 (Holloway et al. 1996).

After the merger of the two SMBH, which is estimated to occur on a time scale of $\sim 10^7$ yr on the pc scale (Zier & Biermann 2001; Biermann et al. 2003), the two jets would be ejected from the merged SMBH along the new spin axis of the SMBH, and hence may face little bending from the ISM, whose rotation axis may be derived from the orbit of the captured galaxy. The rotation axes of the ISM and the merged black hole may be quite

similar for cases when the two black hole masses are not grossly unequal. At the same time, the synchrotron plasma back-flowing from each hotspot would expand into the nearest pre-existing, well established (low-density) secondary lobe. This injection of the back-flowing plasma into the (Z-symmetric) secondary lobe pair would prolong their radio visibility, while the pair of the newly created primary lobes continue to move ahead. In common with the standard spin-flip picture, one could see secondary lobes of greater length than the primary lobes, something that is quite implausible in any type of pure back-flow model. Note that the diffusion of the back-flowing plasma from the primary lobes into the pre-existing secondary lobes would be facilitated through the buoyancy forces acting on the plasma. This effect would be most pronounced in the case when the secondary lobes happen to extend roughly along the steepest ISM pressure gradient, i.e., along the minor axis of the active elliptical galaxy (e.g. Wiita 1978), thus explaining the correlation between secondary lobe direction and optical galaxy morphology noted by Capetti et al. (2002).

Thus, to sum up, the scenario sketched here can provide a fairly natural explanation for the main morphological properties of X-shaped RGs (§1; Fig. 1). Simultaneously, it can account for the strong tendency of XRGs to be associated with relatively weak FR II radio sources (e.g. Leahy & Parma 1992; Capetti et al. 2002). This is because, if the lobes created after the SMBH merger are of very low radio luminosity, and thus have a pure FR I morphology, they would advance subsonically, like a plume of synchrotron plasma (e.g. Gopal-Krishna & Wiita 1988, 2001; Bicknell 1995). As soon as these advancing plumes approach the low-density channels associated with the pre-existing secondary lobes, they would be diverted into those lobes, instead of advancing straight ahead, as do the FR II lobes with jet-driven hot spots. Then no large-scale primary lobes would develop and one would only find a Z-symmetric FR I radio source. On the other hand, very powerful FR II sources will traverse the ISM quickly, and only a small amount of cocoon plasma is likely to flow into the remnant lobes from pre-realignment activity. Thus any bright, reactivated regions of such lobes will typically be much smaller than the newly created lobes; such sources are expected to have somewhat broader than usual cocoons near the host galaxy but would not appear as clearly X-shaped, or winged, RGs. Also recall that only a fraction of Z-symmetric XRGs will be oriented suitably that we can observe the offsets of the secondary lobes, so the number of XRGs with Z-symmetries is certainly significantly larger than the number identified so far.

It is also interesting to note that the primary radio lobes of both sources in Fig. 1 exhibit a mild "C-symmetry". Such a jet bending can be understood in our model as arising from the linear momentum imparted to the radio-loud SMBH by the merged SMBH. Also, just during the merger of the two black holes, the accretion disk and the base of the jet will be destroyed, but will be reestablished a short time later; the consequences of the dip in the

radiation field and the realignment of the beamed emission may entail observable effects.

In the model proposed here, the sources evolve along a Z – X morphological sequence. If basically correct, this picture can provide radio signatures of an impending merger of the SMBHs associated with two colliding galaxies. A Z-symmetric radio morphology would often precede the SMBH merger, which would itself be manifested subsequently by the XRG phenomenon. Another important manifestation predicted is the general relativistic emission of gravitational waves during the SMBH merger (e.g. Rottmann 2001; Zier & Biermann 2001; Chirvasa 2002; Merritt & Ekers 2002; Biermann et al. 2003). We finally note that, in addition to accounting for all the major observational attributes of XRGs, our model can be potentially useful for inferring the sense of spin of the merged SMBH, since its spin would normally be dominated by the orbital angular momentum vector of the infalling core of the captured galaxy (e.g. Zier & Biermann 2002) which, in turn, can be inferred from the observed bending of the secondary lobes into a Z-symmetric form. This is an encouraging prospect, since the possibility of also inferring the spin direction of the SMBH from circular polarization measurements at centimeter wavelengths has recently been discussed in the context of the cores of quasars (Ensslin 2003).
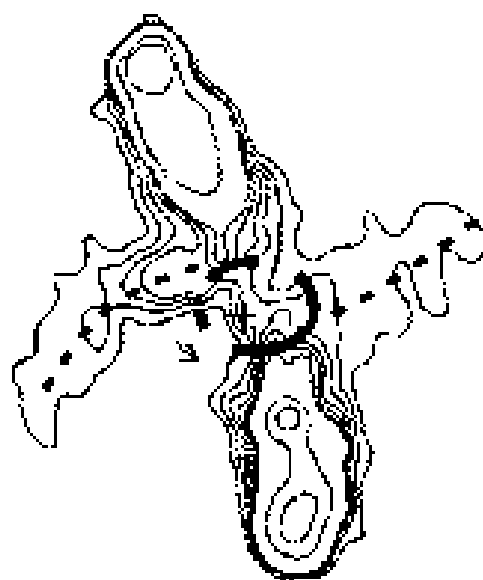
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Fig. 1.— VLA maps of two prominent XRGs are shown: 3C 52 (Leahy & Williams 1984, ©RAS) in the upper panel, and NGC 326 (Murgia et al. 2001, ©ESO) in the lower panel, where several of the contours have been omitted to improve clarity. The second image of 3C 52 on the right in the upper panel illustrates our model schematically. The ridge lines of the two secondary lobes are marked with dotted lines. The partial elliptical ring around the nucleus represents the postulated shell-like features discussed in the text, whose direction of rotation is indicated by the arrow.

3C52

NGC326